Patent Application

of

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for

Apparatus and Method for an Electronically Tuned, Wavelength-Dependent Optical Detector

FIELD OF THE INVENTION

The present invention relates generally to an apparatus and method for an electronically tuned, wavelength-dependent optical detector.

BACKGROUND OF THE INVENTION

Wavelength-dependent optical detectors are essential optical components that are incorporated in a myriad of applications including spectrometers, optical interconnects and optical communications systems.

An existing wavelength-dependent optical detector is the so-called metal-semiconductor-metal (MSM) photodetector. In this device, an interdigitated pair of metal electrodes is deposited on a surface of a semiconductor. Light illuminating the MSM device is absorbed in the semiconductor producing charge carriers that drift to the neighboring metal electrodes when a voltage is applied to the metal electrodes. The resulting light-induced current is amplified and detected by an amplifier. The wavelength-dependence of the MSM device is partially determined by the absorption characteristics of the semiconductor in the MSM device. GaAs is used as the semiconductor for MSM devices in the 800 nm wavelength range. InAlAs deposited on InGaAs is used as the semiconductor for MSM devices in the 1600 nm wavelength range. The prior art teaches that the wavelength-dependence of the MSM device can be further selected by creating a standing wave on the MSM detector and fabricating the MSM device such that metal electrodes have a particular spacing, for example, a quarter of the wavelength of light to be detected.

While such MSM devices have been successfully employed in a variety of applications, a principal limitation of the MSM device is that the wavelength-dependence cannot be dynamically tuned. It is manifest that this is also the case for other optical detectors that are not wavelength-dependent, such as photodiodes and photomultiplier tubes. Prior art solutions to this technical challenge include external means for dynamically tuning the wavelength of light detected. Solutions include monochromators, interferometers, multiplexers/demultiplexers, spatial optical filters, spectral optical filters (including cavity resonators) and diffraction gratings. For example, see US Pat. Nos. 6,583,900, 6,594,410 and 6,597,841. However, the speed with which the selected wavelength can be changed in these approaches is limited when the dynamic tuning is based on mechanical motion, such as that associated with a stepper motor or thermal expansion. This is also the case when the dynamic tuning is based on the propagation of waves (for example, sound) in a medium, such as in an acousto-optic modulator or a dynamic diffraction grating. The response time for dynamic tuning of the wavelength-dependence of the existing optical detectors in conjunction with such

external means is substantially longer than a microsecond and is typically hundreds to thousands of microseconds. A PIN detector with multiple quantum wells can be dynamically tuned with a fast response time; however, such devices only have a coarse tuning capability over a small range of wavelengths and require a large biasing voltage. These limitations in the dynamic tuning of the wavelength dependence of existing optical detectors are particularly problematic in existing or proposed optical communications systems based on Wavelength Division Multiplexing (WDM).

In optical communications systems based on WDM, a combination of time dependent multiplexing (interleaved packets of information), frequency dependent multiplexing (information communicated using multiple, different wavelengths) and/or spread spectrum (wideband) encoding techniques such as code division multiple access are used. Systems include coarse wavelength division multiplexing (CWDM) and dense wavelength division multiplexing (DWDM). Recent proposals include 80 channels utilizing a wavelength range centered around 1550 nm (193,300 GHz) with a channel spacing of approximately 0.4 nm (50 GHz) and optical packets of information spaced on time scales on the order of nanoseconds. Future systems will employ more channels (smaller channel spacing) and packets of information spaced on shorter time scales.

To be useful in detecting packets of information based on wavelength in a WDM system, it is highly desirable to be able to switch the wavelength dependence of the optical detector on times scales on the order of or less than the length of the optical packets of information. This necessitates response times for dynamic tuning of the wavelength dependence of the optical detector of a few nanoseconds or less. Response times of this order are well beyond the capability of most of the existing solutions. The alternative, involving a plurality of wavelength-dependent optical detectors with slow dynamic tuning response times, would be expensive and difficult to manufacture and maintain. Each wavelength in the optical system would require a separate detector, the related electronics for amplifying detected signals, as well as a fixed optical filter capable of resolving the small band of

wavelengths corresponding to the channel spacing. For example, see US Pat. Nos. 5,546,209, 5,910,851, 6,307,660 and 6,556,321.

As a consequence, there is a need for a wavelength-dependent optical detector that can be dynamically tuned with a response time less than a few nanoseconds for WDM applications, and more generally with a response time less than a microsecond for other applications. It would also be advantageous if the wavelength-dependent optical detector could be dynamically tuned to resolve the narrow channel spacing in WDM systems yet have a wide tuning range. Furthermore, it would be advantageous if such a wavelength-dependent optical detector with fast dynamic tuning were electronically controlled using a low voltage thereby allowing ease of integration with other components.

OBJECTS AND ADVANTAGES

In view of the above, it is a primary object of the present invention to provide an apparatus and method for a wavelength-dependent optical detector that can be dynamically tuned over a wide range with a response time of less than a few nanoseconds. More specifically, it is an object of the present invention to provide an electronically tuned, wavelength-dependent optical detector.

These and numerous other objects and advantages of the present invention will become apparent upon reading the following description.

SUMMARY

The objects and advantages of the present invention are secured by an apparatus and method for an electronically tuned, wavelength-dependent optical detector. The electronically tuned, wavelength-dependent optical detector is a modified MSM photodetector. In the modified MSM device, a comb-like metal electrode, comprising at least five, substantially parallel arms with a fixed spacing from each other and having a common voltage, is deposited on a surface of

a semiconductor. At least four metal electrodes, interdigitated with the comb-like metal electrode are also deposited on the surface of the semiconductor. Each of the metal electrodes is connected to a voltage means that applies a control voltage to each metal electrode. By applying a set of control voltages to the metal electrodes using the voltage means, a wavelength to be detected in a stream of light illuminating the modified MSM device is selected.

In one embodiment of the invention, the comb-like metal electrode in the modified MSM device is connected to an amplifier.

In another embodiment, an opaque coating is deposited on parts of the surface of the modified MSM device thereby grouping the arms of the comb-like metal electrode and the metal electrodes into pairs.

In another embodiment, the semiconductor in the modified MSM device is selected based on the wavelengths to be detected. GaAs is used for MSM devices in the 800 nm wavelength range. InAlAs deposited on InGaAs is used for MSM devices in the 1600 nm wavelength range.

In another embodiment, a plurality of modified MSM devices are used in an optical system where a stream of light comprised of multiple wavelengths is at least partially spatially segregated using a dispersion device.

In another embodiment, a standing wave generator is used to produce a spatially varying light intensity of the surface of the modified MSM device. By appropriately positioning the modified MSM device relative to the varying light intensity and applying a set of voltages to the metal electrodes using the voltage means, the wavelength to be detected is selected.

In another embodiment, the standing wave generator is an interferometer, and position of fringes in the spatially varying light intensity on the electronically tuned, wavelength-dependent optical detector is adjusted by varying the optical path-length difference in the

interferometer. In addition, the wavelength spacing of the detected channels is adjusted by changing the optical path-length difference.

In another embodiment, the standing wave generator is an interferometer that interferes two beams separated by an angle on the MSM device, and the relative phase of the fringes in the spatially varying light intensity and the channel spacing is adjusted by varying the optical path-length difference in the interferometer.

In yet another embodiment, the standing wave generator is an interferometer that interferes two beams separated by an angle on the MSM device, and period of the fringes in the spatially varying light intensity is adjusted by varying the angle of incidence of the interfered beams.

A detailed description of the invention and the preferred and alternative embodiments is presented below in reference to the attached drawing figures.

BRIEF DESCRIPTION OF THE FIGURES

Fig. 1	is a diagram illustrating a side view of an apparatus according to the invention.
Fig. 2	is a diagram illustrating a top view of an apparatus according to the invention.
Fig. 3	is a diagram illustrating a top view of another embodiment of an apparatus according to the invention.
Fig. 4	is a diagram illustrating a side view of another embodiment of an apparatus according to the invention.
Fig. 5	is a diagram illustrating an optical system incorporating an apparatus according to the invention.
Fig. 6	is a diagram illustrating an experimental set-up.
Fig. 7.	is a diagram showing the measured photocurrent as a function of wavelength.
Fig. 8	is a diagram illustrating a biasing configuration relative to the fringes of an interference pattern for an apparatus according to the invention.

Fig. 9 is a diagram illustrating a biasing configuration relative to the fringes of two interference patterns for an apparatus according to the invention.

Fig. 10 is a diagram illustrating an experimental set-up.

DETAILED DESCRIPTION OF THE EMBODIMENTS

A side view of an embodiment of the invention is illustrated in Fig. 1. A stream of light **110** comprising at least one wavelength illuminates an electronically tuned, wavelength-dependent optical detector apparatus **100**. The apparatus **100** is a modified MSM photodetector. The apparatus **100** has a comb-like metal electrode **114**, comprising at least five, substantially parallel arms with a fixed spacing from each other and maintained at a common voltage. The parallel arms of metal electrode **114** are deposited on a surface of a semiconductor **112** . At least four metal electrodes **118, 120, 122** and **124**, interdigitated with the comb-like metal electrode **114** are also deposited on the surface of the semiconductor **112**. Each of the metal electrodes **118, 120, 122** and **124** is connected by an electrical connection **128** to a voltage means **130**, such as a power supply, that applies a control voltage to each metal electrode **118, 120, 122** and **124**. In an alternative embodiment, the voltage means **130** is flip-chip bonded to the semiconductor **112**. The stream of light **110** is absorbed in the semiconductor **112** producing charge carriers that drift to the neighboring metal electrodes **118, 120, 122** or **124** or the arms in the comb-like metal electrode **114** when the control voltage is applied to each of the metal electrode **118, 120, 122** and **124**.

Fig. 2 illustrates a top view of the apparatus **100**, with the comb-like metal electrode **114** deposited on the surface of the semiconductor **112**. The comb-like metal electrode **114** has a common connection point **116**. At least four metal electrodes **118, 120, 122** and **124**, interdigitated with the comb-like metal electrode **114**, are deposited on the surface of the semiconductor **112**. The metal electrodes **118, 120, 122** and **124** are connected by the electrical connection **128** to the voltage means **130**.

Fig. 3 illustrates a top view of alternative embodiments of apparatus **150**. In this embodiment, an opaque coating **126** is deposited on the surface of the semiconductor **112** such that the arms in the comb-like metal electrode **114** are paired with one of the metal electrodes **118**, **120**, **122** and **124**. Another alternative embodiment has an amplifier **134** connected **132** to the common connection point **116** of the comb-like metal electrode **114**. In a preferred embodiment, the amplifier **134** is a trans-impedance amplifier. In yet another alternative embodiment, the amplifier **134** is flip-chip bonded to the semiconductor substrate **112**.

Fig. 4 illustrates a side view of alternative embodiments of apparatus **160**. One alternative embodiment has an optional base layer **136**, an optional intermediate layer **138** and an optional top layer **140** deposited in layers located above the surface of the semiconductor **112** and below the layer containing the comb-like metal electrode **114** and the metal electrodes **118**, **120**, **122** and **124**. For wavelengths in the stream of light **110** less than 860 nm, a preferred embodiment has a semi-insulating GaAs semiconductor **112**, a substantially 0.3 micron thick GaAs base layer **136** as a buffer, a substantially 0.3 micron AlGaAs intermediate layer **138** comprising relative proportions of substantially 85% aluminum and 15% gallium in the AlGaAs compound and being substantially 1 micron thick, and an undoped GaAs top layer **140** that functions as the active layer in the apparatus **160** absorbing the stream of light **110**. The intermediate layer **138** in this embodiment serves two functions: it acts as an etch stop for etching through the semiconductor **112**, thereby allowing flip-chip bonding of electronics such as the voltage means **130** and the amplifier **134** to the apparatus **160**, and it acts as a barrier to keep carriers in the top layer **140** thereby improving temporal response of the apparatus **160** when stream of light **110** is absorbed in the top layer **140**.

When the intermediate layer **138** is used as an etch stop layer, after flip-chip bonding of electronics such as the voltage means **130** and the amplifier means **134**, the entire substrate layer **112** can be chemically removed using a selective etch or etches well known to those skilled in the art, with the etch substantially stopping when layer **138** is reached. In this case, stream of light **110** can impinge on the intermediate layer **138** from the bottom, which may be

convenient since the flip-chip bonded electronics might otherwise get in the way of the stream of light **110** when the stream of light **110** is incident from above as shown in Fig. 4.

For wavelengths in the stream of light **110** substantially larger than 850 nm but less than 1650 nm, such as wavelength in the range 1200-1600 nm commonly used in telecommunications, a preferred embodiment has a semi-insulating InP semiconductor **112**, an InP base layer **136** as a buffer, an undoped InGaAs intermediate layer **138** (comprising substantially 47% In and substantially 53% Ga and As) that functions as the active layer in the apparatus **160** absorbing the stream of light **110**, and a thin InAlAs top layer **140** that increases the Schottky barrier height in the apparatus **160** and thereby reduces the leakage current that flows even when the stream of light **110** does not illuminate the apparatus **160**.

Those skilled in the art will recognize that the details of the wafer structure can be modified for other applications of the invention in spectroscopy, optical interconnects, optical sensing and optical detection since the range of wavelength that can be detected with the apparatus **160** are confined to the absorption range of the semiconductor in the active layer of the apparatus **160**.

As described thus far, the apparatus **160** cannot distinguish between two wavelengths so long as they are within the absorption range of the semiconductor in the active layer of the apparatus **160**. For example, an apparatus with a GaAs active layer cannot distinguish 850 nm from 840 nm. To further distinguish the wavelength in the stream of light **110** to be detected in this invention, rapid, electronic tuning of the apparatus **160** occurs by varying the control voltage applied by the voltage means **130** to each of the metal electrodes **118**, **120**, **122** and **124**. Temporal response of the apparatus **160** to a change in the control voltage is determined by resistance-capacitance (RC) time constant. For the apparatus **160** with the arms in the comb-like metal electrode **114** and the metal electrodes **118, 120**, **122** and **124** having tens of micron length **113** (in Figs. 2 and 3) and with micron spacing **115** (in Figs. 2 and 3) between the arms in the comb-like metal electrode **114** and the metal electrodes **118, 120,** **122** and **124**, and width **117** of comb-like metal electrode **114** and the metal electrodes **118,**

120, **122** and **124**, capacitance of the apparatus **160** is less than several hundred fF. For the MSM device **100** in Fig. 2 with 0.8 micron electrode spacing **115** and width **117** and with interdigitated pattern covering total area of 100 micron length (not shown) by 52 micron width (not shown), the capacitance is theoretically 167.25 fF. For the MSM device **100** in Fig. 2 with 0.8 micron electrode spacing **115** and width **117** and with the interdigitated pattern covering total area of 40 micron length (not shown) by 26.4 micron width (not shown), the capacitance is theoretically 33.5 fF. Referring back to Fig. 4, in conjunction with low resistance of the apparatus **160**, the temporal response of the apparatus **160** to change in the control voltage is less than a nanosecond. The rapid, electronic tuning of the apparatus **160** in this invention is further described below.

Fig. 8 schematically illustrates the electronic tuning of the wavelength in this invention. Here a spatially varying light intensity **400** corresponding to a wavelength in the beam of light **110** is shown on the surface of the apparatus **100** with a fringe spacing or separation between maxima **410** and minima **412** in the spatially varying light intensity that corresponds to four times the summation of the spacing **115** between and the width **117** of the comb-like metal electrode **114** and the metal electrodes **118**, **120**, **122** and **124** in the apparatus **100**. Note that it is also important that the apparatus **100** be appropriately positioned relative to the spatially varying light intensity. In this example, the locations of the maxima **410** and the minima **412** in the spatially varying light intensity **400** are aligned with the locations of the comb-like metal electrode **114**. If a negative control voltage is applied by the voltage means **130** to the metal electrodes **118** and **124**, and a positive control voltage is applied by the voltage means **130** to the metal electrodes **120** and **122**, the wavelength in the stream of light **110** that gives rise to the spatially varying light intensity **400** in Fig. 8 will give rise to zero net current and thus will not be detected. In contrast, the same control voltages will allow a neighboring wavelength with maxima **414** and minima **416**, shown by the dashed line in Fig. 9, to produce a net current and therefore to be detected.

In principle, due to its symmetric structure, the current-voltage characteristic of the ideal electronically tuned, wavelength-dependent optical detector apparatus **100** has positive/negative symmetry with respect to the control voltage applied by the voltage means **130** to the metal electrodes **118, 120, 122** and **124**. In practice, variations in fabrication may necessitate different voltages when wavelength-dependent optical detector apparatus **100** is illuminated by stream of light **110** with fringe intensity variation **400**.

The detection of multiple wavelengths with a single apparatus **100** is enabled by this invention by increasing the number of metal electrodes **118, 120, 122** and **124** and the corresponding arms in the comb-like metal electrode **114** in the apparatus **100**. The detection of multiple wavelengths with a single apparatus **100** is further enabled by appropriately positioning the apparatus relative to the spatially varying light intensity on the surface of the apparatus **100**, i.e., by selecting the appropriate spatial phase relation, and by applying the appropriate control voltage to each metal electrode **118, 120, 122** and **124**.

Fig. 10 illustrates in an exemplary embodiment how a standing wave generator such as an interferometer **500** is used to produce the spatially varying light intensity and to select relative phase of this spatially varying light intensity on wavelength dependent optical detector **504**. A beam of light **502** is divided into two beams of light **506** and **508** by a beam splitter **510**. Beam of light **508** is reflected off of mirror **512**. Beams of light **506** and **508** pass through a lens **514** and are incident on the wavelength dependent optical detector **504** with an incident angle **516** relative to the normal **518** of the wavelength dependent optical detector **504**. Beams of light **506** and **508** interfere due to a relative difference **520** in their optical path lengths. Such a path length difference **520** results in a time delay between the two beams **506** and **508** because of the additional time taken for light to propagate through the additional distance **520** in the path of beam of light **508.** As a result of this delay and the incident angle **516** relative to the normal to the wavelength dependent optical detector **504**, when the wavelength changes, the spatially varying light intensity substantially moves, corresponding to a change of the relative phase of the spatially varying light intensity. There

is also a change in period of the spatially varying light intensity, although for small wavelength changes the variation in position of the spatially varying light intensity (and thus the relative phase) is more important for the operation of the wavelength-dependent optical detector **504**. Additional means for forming such spatially varying light intensities on the surface of detectors with multiple elements are discussed in D. A. B. Miller, "Laser Tuners and Wavelength-Sensitive Detectors Based on Absorbers in Standing Waves," IEEE Journal of Quantum Electronics, **30**, 732-749 (1994), which is hereby incorporated by reference.

The dependence of the spacing between fringes in the spatially varying light intensity on the incident angle **516** of the two interfered beams of light **506** and **508** can be conceptually understood in terms of a plane wave with a fixed wavelength λ incident at an angle Ω relative to the normal of a flat mirror. The effective period of the standing wave pattern projected on the mirror is $\lambda/\sin(\Omega)$. Since $\sin(\Omega)$ is always less than one, if beams of light **506** and **508** are incident at incident angle **516** (equal to Ω) with respect to the wavelength dependent optical detector **504**, the fringe width in the interference pattern, given by $\lambda/(2\sin(\Omega))$, is increased compared to half a wavelength $\lambda/2$.

The theory behind the wavelength-dependent optical detector in this invention is described below for two illustrative examples.

Suppose we want the electronically tuned, wavelength-dependent optical detector in this invention to distinguish between two different wavelengths. As described above, the apparatus **100** with the comb-like metal electrode **114** and the four metal electrodes **118**, **120**, **122** and **124** is required. This is the minimum modified MSM device section size. Take the wavelength in the spatially varying light intensity aligned with the metal electrodes **118**, **120**, **122** and **124**, such as that corresponding to the dashed curve **414** in Fig. 9, to be 860 nm. This is the wavelength to be detected. Metal electrodes **120** and **122** at the positive portions of the cycle corresponding to this wavelength have positive control voltage. Metal electrodes **118** and **124** at the negative portions of the cycle corresponding to this wavelength have negative control voltage. The relative phase between spatially varying intensity pattern for this

wavelength and spatially varying intensity pattern for the neighboring wavelength that is not to be detected, such as the solid curve in Figs. 8 and 9, is taken to be $\pi/2$. Furthermore, the neighboring wavelength that is not to be detected is taken to be 860.24 nm. For an arbitrary wavelength λ, constructive superposition at each metal electrode **118, 120, 122** and **124** requires

$$m\lambda = (m + \phi/2\pi)860.$$

Taking m = 896 as an illustrative example and rearranging we have

$$\phi = 2\pi[896(\lambda - 860)/860].$$

The integrated intensity I over one period (0 to 2π) is $I = I_1 - I_2$, where $I_1 \propto \int (1 + \sin(\theta - \phi))d\theta$ evaluated between 0 and π and $I_2 \propto \int (1 + \sin(\theta - \phi))d\theta$ evaluated between π and 2π. After some math, we find that

$$I \propto 4 \cos(\phi) = 4 \cos(2\pi[896(\lambda - 860)/860]).$$

For λ = 860 nm, I = 1. For λ = 860.24 nm, I = 0. This value of I corresponds to $\phi = \pi/2$, the phase shift between the two spatially varying light intensity patterns of the two wavelengths that we wished to discriminate between. Since the spatially varying light intensity pattern corresponding to the wavelength we wanted to detect (860 nm) is aligned with the metal electrodes **118, 120, 122** and **124**, this result is tantamount to saying that the phase shift of the spatially varying light intensity pattern that we do not want to detect, i.e., the one corresponding to a wavelength of 860.24 nm, relative to the metal electrodes **118, 120, 122** and **124** is $\pi/2$. This, in turn, indicates the relative placement and biasing of the metal electrodes **118, 120, 122** and **124** in the apparatus **100** relative to the spatially varying light

intensity corresponding to this wavelength. If we now wish to use the same detector to detect light of wavelength 860.24 nm and not detect light of wavelength 860 nm, we merely need to change the biasing of the fingers. Biasing metal electrodes **118** and **120** positively and metal electrodes **122** and **124** negatively will cause wavelength 860.24 nm to be detected and wavelength 860 nm not to be detected. This change in biasing corresponds to shifting the biasing pattern by a phase of $\pi/2$. Hence merely changing the biasing of the electrodes in the detector changes the wavelengths that it will detect and those that it will not detect.

To discriminate between 4 wavelengths (for example, 860 nm, 860.24 nm, 860.48 nm and 860.72 nm), a second minimum modified MSM device section is required. Thus, there are now 8 metal electrodes, where each of the MSM device sections has electrodes such as **118**, **120**, **122** and **124**. One of the minimum modified MSM device sections is placed in the interference pattern between the beams such that the relative phase between the spatially varying intensity patterns of two adjacent wavelengths is $\pi/4$. The second minimum modified MSM device section is placed in the interference pattern between the beams such that the relative phase between the spatially varying intensity patterns of two adjacent wavelengths is $3\pi/4$. Repeating the previous calculation with $m = 448$ we find that

$$I \propto \cos(2\pi[448(\lambda - 860)/860]) + \cos(2\pi[1344(\lambda - 860)/860]).$$

For $\lambda = 860$ nm, $I = 2$. For $\lambda = 860.24$ nm, $I = 0$. For $\lambda = 860.48$ nm, $I = 0$. For $\lambda = 860.72$ nm, $I = 0$. Once again, the arguments of the cosine functions at the wavelengths that are not to be detected correspond to the relative phases between the spatially varying light intensities (in this example, multiples of $\pi/4$ and $3\pi/4$). Once again, these phases indicate the relative placement and biasing of the metal electrodes, such as **118**, **120**, **122** and **124**, in the apparatus **100** relative to the spatially varying light intensities corresponding to these wavelengths.

This invention can be generalized to discriminate between an arbitrarily large number of wavelengths. As such, this invention enables a wide tuning range. The results are summarized in Table I.

Table I. Generalized technique for electronically tuned, wavelength detection using modified MSM optical detectors.

Number of Wavelengths to be Discriminated	Number of Minimum MSM device Sections	Relative Phase (Where to Place the MSM Device Sections)	Number of Metal Electrodes
2	1	$\pi/2$	4
4	2	$\pi/4$, $3\pi/4$	8
8	4	$\pi/8$, $3\pi/8$, $5\pi/8$, $7\pi/8$	16
2^N	2^{N-1}	$\pi/2^N, \ldots, (2^N-1)\pi/2^N$	2^{N+1}

Fig. 5 shows an illustration of an embodiment of an optical system **200** that uses this invention. A stream of light **210** comprised of a plurality of wavelengths and containing information is at least partially spatially segregated by a dispersion device **212** into three optical beams **214, 216** and **218** each containing at least a wavelength and possibly a range of wavelengths. Suitable dispersion devices include, among others, a prism, a diffraction grating or an arrayed waveguide grating. The optical beams **214, 216** and **218** are collimated by a lens **220** and illuminated onto electronically tuned, wavelength-dependent optical detectors **224, 226** and **228**, each of which is the same as the apparatus **160** as shown in Fig. 4. The optical detectors **224, 226, 228** are each connected **230, 232** and **234** to voltage means **236, 238** and **240**. In an alternative embodiment, the voltage means **236, 238** and **240** are incorporated in

the optical detectors **224**, **226**, **228**. While this embodiment could use a standard photodetector that is neither wavelength-dependent nor dynamically tunable, such as those known in the prior art, the electronically tuned, wavelength-dependent optical detector of this invention still offers an advantage. In particular, the electronically tuned, wavelength-dependent optical detectors **224**, **226** and **228** are able to detect the range of wavelengths in each beam **214**, **216** and **218**, thereby reducing the number of optical detectors **224**, **226** and **228** in the optical system **200**. In addition, in this example the dispersion device **212** provides coarse dispersion of the stream of light **210** and the optical detectors **224**, **226** and **228** provide fine wavelength resolution. Standing wave generators **222**, **225** and **227** are inserted between the lens **220** and optical detectors **224**, **226** and **228** thereby producing a spatially varying light intensity on optical detectors **224**, **226** and **228**. Interferometer **500** is suitable for standing wave generators **222**, **225** and **227**. As described in the theory behind this invention described above, by appropriately positioning the spatially varying light intensity on optical detectors **224**, **226** and **228** such that the metal electrodes **118**, **120**, **122** and **124** have the appropriate spatial phase relationship with the spatially varying light intensity and by applying the appropriate control voltage to each of the metal electrodes **118**, **120**, **122** and **124**, particular wavelengths in the stream of light **210** can be selected for detection.

The interferometer **500** used as standing wave generators **222**, **225** and **227** is also used to adjust the channel spacing. In an interferometer, a larger the optical path-length difference in the arms of the interferometer will result in a different phase for the fringes in the resultant interference pattern for a given wavelength since $\phi = 2\pi n\Delta d/\lambda$, where ϕ is the phase difference between the light in the arms of the interferometer that gives rise to the interference, n is the index of refraction, λ is the wavelength and Δd is the path-length difference. As described in the theory behind this invention described above, for discrimination between two wavelengths λ_1 and λ_2 a relative phase of $\pi/2$ is desired. In this case, the phase difference ϕ is

$$\frac{2\cdot\pi\cdot n\cdot\Delta d}{\lambda_1}-\frac{2\cdot\pi\cdot n\cdot\Delta d}{\lambda_2}=\frac{\pi}{2}.$$

Dividing both sides of this equation by 2π yields

$$n\cdot\Delta d\cdot\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)=n\cdot\Delta d\cdot\left(\frac{\lambda_2-\lambda_1}{\lambda_1\cdot\lambda_2}\right)=n\cdot\Delta d\cdot\left(\frac{\Delta\lambda}{\lambda_1\cdot\lambda_2}\right)=\frac{1}{4}.$$

For telecommunication applications, wavelengths λ_1 and λ_2 are almost the same and can be taken to be approximately equal to wavelength λ, in this case the average of wavelengths λ_1 and λ_2. As a result, the required path length difference Δd is inversely proportional to $1/\Delta\lambda$. Thus, increasing the optical-path length difference in the interferometer or the incident angle **516** of the beams of light **506** and **508** reduces the channel spacing. In addition, as mentioned previously in Fig. 10, the period of the fringes in the interference pattern is a function of the incident angle **516** given by $\lambda/(2\sin(\Omega))$.

This embodiment of this invention is further illustrated in Fig. 6, which shows a schematic of the experimental setup **300** used to perform measurements with an electronically tuned, wavelength-dependent optical detector **346** of this invention. A stream of light **312** is produced by a light source **310**. A tunable Ti-Sapphire laser is suitable. The light **312** passes through a chopper **314**, to enable sensitive lock-in detection, and lenses **316** and **318**, which determine the size of the interference pattern on the optical detector **346**. The light **312** passes through an attenuator **320** and is directed along two paths in the Michelson interferometer by a 50/50 beam splitter **322**. The two paths have path lengths **324** and **328**. As noted above, the path length difference Δd, which is twice the difference of path lengths **324** and **328**, partially determines the phase difference ϕ and the channel spacing. After reflecting off of mirrors **326** and **330,** the light passes through a beam splitter **332**, a focal lens **344** and illuminates optical detector **346**. While not shown in Fig. 6, two beams in the stream

of light **312** illuminate the optical detector **346** at an angle, as shown in Fig. 10, producing an interference pattern (not shown) on the optical detector **346**. Referring back to Fig. 6, the angle between the two beams is controlled by tilting mirrors **326** and **330**. In practice, the tilt, the path length difference Δd and wavelength λ_1 are fixed. As wavelength λ_2 varies, the relative phase is varied. The optical detector **346** is connected **348** to a voltage means **350**. As disclosed in this invention, the position of the optical detector **346** relative to the fringes in the interference pattern is important. This is determined in this experimental setup **300** using an LED **342** to produce light **341** that is focused by a lens **340**, passes through beam splitters **334** and **332**, the focal lens **344** and illuminates the optical detector **346**. The light reflected from the optical detector **346** passes through the focal lens **344**, through the beam splitters **332** and **334**, and is focused by a lens **336** onto a CCD camera **338**.

An electronically tuned, wavelength-dependent optical detector **346** of this invention has been fabricated where the spacing **115** and the width **117** of the comb-like metal electrode **114** and metal electrodes **118**, **120**, **122** and **124** are both 0.8 micron. The interdigitated pattern covers a 40 micron by 13.6 micron area. Fig. 7 shows the results of measurements performed using the optical detector **346** to distinguish two neighboring wavelengths. Positive control voltage of 2.1 V was applied to the metal electrodes **120** and **122** in the optical detector **346** by the voltage means **350** and negative control voltage of –1.25 V was applied to the metal electrodes **118** and **124** in the optical detector **346** by the voltage means **350** as illustrated schematically in Figs. 8 and 9. The optical detector **346** is sensitive to the wavelength labeled "On" at 807.54 nm and is insensitive to the wavelength labeled "Off" at 808.33 nm. The theoretical sinusoidal response of the optical detector **346** is also shown. The demonstrated channel spacing of 0.76 nm is sufficient to enable a 365 GHz channel spacing in a WDM system. Additional experiments were able to resolve a channel spacing of 50 GHz. The channel spacing capability of the experimental setup **300** is limited by the line width and discontinuous tuning of the light source **310** not the capabilities of the optical detector **346**.

The electronically tuned, wavelength-dependent optical detector in this invention has numerous advantages with respect to wavelength-dependent optical detectors in the prior art. It is capable of rapid tuning for multiple wavelengths with sub-nanosecond switching time. Electronic tuning is at low voltages (unlike devices with an external micro-machined optical filter) allowing easy integration with CMOS electronics. The wavelength-dependence is substantially insensitive to temperature variations (unlike devices with an external cavity-based optical filters). The channel spacing can be adjusted dynamically. The wavelength-dependence of the apparatus **100** is integrated into the apparatus **100**, obviating the need for an external optical filter. And, finally, by adding additional metal electrodes **118**, **120**, **122** and **124** and arms to the comb-like metal electrode **114** the electronically tuned, wavelength-dependent optical detector is capable of a wide tuning range limited only by the absorption characteristics of the semiconductor in the active layer of the apparatus **100**.

In view of the above, it will be clear to one skilled in the art that the above embodiments may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.